G

APPENDIX G

LDR FM Hybrid Compatibility with Host FM Analog Signal

Lucent Digital Radio, Inc.

20 Independence Blvd

Warren, NJ 07059, USA

Multimedia Perception Assessment Center

Host compatibility: Subjective testing and expert listening results (Test L)

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This report describes procedures and results from one of two subjective tests conducted at Lucent's Multimedia Perception Assessment Center located in Holmdel, New Jersey. This report includes results from both end-user testing and expert listening. End-user testing was conducted between November 10th and November 23rd. Expert listening was performed in Red Hill, Illinois during the same time frame in order to (a) assess the extent of impairments caused by digital interference, and (b) to identify the specific impairments that contributed to end-user's dissatisfactions. Although results from the end-user study are the main focus of this report, supporting information obtained from expert listening is also included. It is important to note that results from expert listening represent the opinion of one person. Thus, they may not precisely overlay the results found in the end-user study, nor may they necessarily represent the opinion of the general population.

The primary goal of Study L was to characterize the analog component audio quality of the IBOC-FM system when multipath fading was introduced into the signal. Four multipath scenarios were introduced: (a) urban moderate Rayleigh (referred to as urban moderate); (b)urban fast Rayleigh (urban fast); (c) rural fast Rayleigh (rural fast) and (d) terrain obstructed fast Rayleigh (terrain). Additionally, there was a condition in which no multipath was introduced (non-fading channel). Five FM receivers were used to receive the FM portion of the IBOC-FM transmission: (a) Delphi Delco mobile receiver, (b) Ford mobile receiver; (c) Panasonic boom-box; (d) Denon home receiver; and (e) Pioneer SX205 home receiver. When dynamic multipath fading was introduced, however, only the mobile receivers were selected for analysis. This is appropriate because mobile receivers usually operate in dynamic multipath environments, whereas home receivers do not.

Four sound samples were played for participants. Two were provided by the NRSC DAB Subcommittee as recommended critical test cuts: a 10 s Pearl Jam cut (referred to as "Rock"); and an 11 s Susan Vega cut ("Speech"). The third was 5 s of silence (referred to as "Silence"), and the fourth was a 10 s cut of a Hayden symphony ("Classical"), taken from the EIA SQAM disc.

Sixteen participants listened to 100 sound-sample pairs, each sample lasting from 5 to 10 seconds. Half of the samples were FM without DAB sidebands (referred to as FM-Only); the other half were FM signals plus DAB (referred to as IBOC-FM). Listening was conducted in sound rooms that were configured to acoustically simulate an extremely quiet environment (28-35 dBA).

3.1 Trained Listeners

- Trained listeners reported that IBOC-FM sounded the same as or slightly better than FM-Only half of the time. The other half of the time, they reported that IBOC-FM sounded somewhat worse than FM-Only. However, in 68% of these cases they reported that the IBOC-FM sounded only "*slightly worse*" than FM-Only.

- Listeners were most critical of IBOC-FM in the urban moderate condition, and least critical of IBOC-FM in the urban fast and obstructed terrain multipath conditions.

- Preference for FM-Only or IBOC-FM depended on multipath profile and receiver (see Figures 2a and 2b):

    1. *Dephi*: The FM-Only and IBOC-FM were rated similarly in all conditions.

    2. *Ford:* FM-Only was preferred slightly to IBOC-FM in both the Urban Moderate Rayleigh and Urban Fast Rayleigh conditions. In the Rural Fast Rayleigh and Terrain Obstructed Fast Rayleigh, FM-Only and IBOC-FM were rated similarly.

    3. *Panasonic:* FM-Only was preferred slightly to IBOC-FM in all conditions.

    4. *Denon:* As with the Delphi, the FM-Only and IBOC-FM were rated similarly in the No Multipath condition.

    5. *Pioneer:* FM-Only was preferred slightly in the No Multipath condition.

3.2 Expert Listener

- Performance differences between FM and IBOC-FM were attributed to 3 main impairments:
    1. **"static clicks"** referring to short duration broadband sound bursts;
    2. **"swooshing"** referring to short duration broadband noise fluctuations, ("Swooshing" and "static clicks" were related. If both were present, the "static click" occurred during the peak of a "swooshing" fluctuation);
    3. **"hiss"** referring to constant high-pitched broadband noise.

- In over half of the comparisons, IBOC-FM was rated the same or better than FM-Only. IBOC-FM was preferred most strongly in the urban moderate condition.

- In the absence of multipath profile, the only impairment that affected ratings was hiss. Hiss only occurred on the Panasonic Boom-Box and the Pioneer SX205 home receiver for IBOC, but never occurred on FM-Only.

- On all other multipath profiles (i.e. urban moderate, urban fast, rural fast, terrain), static clicks and swooshing determined which sample was preferred.

4.1 Sound file processing, facilities and playback

All recordings were supplied by Lucent Digital Radio. Recordings were parsed into individual sound samples for playback to participants. Listening was conducted in 8'3" x 8'3" sound booths. These booths maintained an ambient room-noise level of between 28 and 35 dBA. A PC monitor and mouse, also located in each room, were used by participants to answer questions about audio quality. The CPUs were located in the control rooms, eliminating computer-fan noise from the test rooms. A custom GUI employed in all of MPAC's subjective testing was used for presenting stimuli and collecting responses.

Samples were presented to subjects via Sennheiser HD 600 headphones connected to a Turtle Beach Pinnacle Pro sound card. This arrangement provided accurate (linear) playback of the recordings. The HD 600 is an open-back headphone. Accordingly, participants were seated in acoustically isolated sound-booths, to prevent background noise from leaking into the sets.

Having participants listen over headphones ensured that environmental noise and speakerphone distortion minimally interfered with their ability to hear small differences in audio quality. However, it is important to point out that results from this test may not predict how participants would judge audio quality in all situations, especially if samples were presented over loudspeakers. We believe that listening over headphones actually encouraged participants to be more discriminating, thus creating a highly and perhaps overly sensitive test of audio quality.

4.3 Participant selection

Eight males and eight females participated as trained listeners. Participants varied in age, but were all under the age of 45. Limiting the participant population to under age 45 minimized the chance of participants having high-frequency hearing-loss (which generally begins to occur for males in their mid-forties). As well as screening for age, participants were chosen based on their ability to complete listening tasks over multiple sessions. Since the NRSC System Test Guidelines did not specifically recommend using expert listeners for testing *impaired* sound samples, participants were not selected based on previous audio experience and/or musical expertise. However, since participants were chosen from the general public, they underwent a rigorous pre-test to ensure that they could reliably identify small differences between sound samples (see Section 4.4).

4.4 Participant Training

Before screening, participants were given information about the kinds of impairments they would hear during the test. Additionally, they were shown how to use the data collection software for the screening pre-test.

Participants were presented with an example of each type of the four sound samples (Rock, Classical, Speech and Silence). Samples were either played over loudspeakers (when training was done with a group) or over the HD-600 headphones (when training was done individually). Several degraded examples were provided. Artifacts such as static, hissing, popping, clicking, fading, and variation in tonal quality were identified. Participants were shown how to play samples multiple times. They were informed that during the test they could replay the three sounds as often as they pleased but could not go back to the sounds once they began to answer the questions. They were also told that one of the sample sounds would always be identical to the reference but that sometimes both samples would be the same as the reference.

The experimenter then demonstrated a trial. Following the demonstration, participants were asked to decide if Sample A, Sample B or both were the same as the Reference. They were then shown how to use the software to register these responses. The trainer suggested that participants write their answers down for each trial, and then enter the responses into the program. This strategy would allow them to rate the samples as they played them, and did not require them to rely solely on their memory.

4.5 Screening procedure

Participants completed 25 trials during the screening test. For each trial, participants were presented with a "Reference" sample (see NRSC Guidelines and Memoranda for detailed description of "reference" recordings) and 2 additional sound samples. These 2 sound samples (A and B) consisted of the Reference (again) and an impaired sound sample (either an IBOC-FM or FM-ONLY sound sample with multipath channel interference). All sound samples in the screening test were taken from those used in Test L. Thus, they were representative of the samples that participants would encounter throughout the testing program. In each case participants were asked to identify the sample that was identical to the Reference, and the sound sample that differed from the Reference. Participants were encouraged to play all three samples as often as required before rendering their judgement. Of the 25 tasks, 10 samples contained impairments that were reasonably easy to discern; 10 contained impairments that were difficult to discern; and 5 contained samples that were identical (i.e., A was the same as the Reference and B was also the same as the Reference sound sample.) Participants rated the samples on a 7-point ITU-R recommended scale, indicating whether they heard a difference, and the extent of the difference (-3 = Sample A is much better than the reference; -2 = Sample A is better than the Reference; -1= Sample A is slightly better than the Reference; 0 = Sample A is the same as the Reference; -1 = Sample A is slightly worse than the Reference; -2 = Sample A is worse than the Reference; -3 = Sample A is much worse than the Reference).

For the 25 tasks, subjects answered 50 questions (i.e., there were two comparisons per task). If participants (a) gave correct answers 90% of the time, and (b) did not miss any of the 20 questions for the 10 most obvious comparisons, it was decided that they could reliably hear impairments and were asked to continue testing. Appendix 1 lists individual participant numbers who were included in the study, and their score in the screening procedure.

4.6 Testing Procedure

Following successful screening, participants proceeded to the actual test procedure. At this time participants were instructed that there would no longer be a Reference, and that Sample A and Sample B would be rated relative to each other.

In Test L, participants listened to 100 sound-sample pairs, in blocks of 25 sample-pairs. Presentation of sample-pairs was randomly determined, and presentation of the single sound samples within the sound-pairs was randomly alternated (e.g., half of the sound-pairs were presented as IBOC/FM, the other half were presented as FM/IBOC). The random ordering of tasks was designed to ensure that the effects of fatigue were minimized, and to ensure that the effect of presentation order would not benefit one type of sample over another. Thus, for a single trial, participants would first click on a button which initiated playback of first Sample A and then Sample B. After this initial playback, participants could click a button labeled Sample A to replay the Sample A wave file (*.wav) or click on a button labeled Sample B, to replay the Sample B wave file. In order to complete the task, participants were asked to indicate whether they felt Sample A was better than Sample B, and to indicate the extent of their preference. As with the pre-screening, they were encouraged to play sound samples as many times as required before rendering judgment. Although NRSC guidelines recommend using a "3-point" scale, participants were instead instructed to rate sound samples on the 7-point ITU-R recommended scale (+3 = Sample A is much better than B; +2 = Sample A is better than B; +1 = Sample A is slightly better than B; 0 = Sample A is the same as B; - 1 = Sample A is slightly worse than B; -2 = Sample A is worse than B; -3 = Sample A is much worse than B.) Because the impairments under test were often very minor, this 7-point scale allowed participants to make finer-grained distinctions between samples. Thus, participants were given a way to indicate that they heard an extremely small difference between the samples. Of course, they could also indicate that they heard a very large difference by rating the second sample a +3 or a – 3.

Participants worked individually on PCs, thus they were able to judge the audio quality of the sound samples at their own pace. Although they were allowed to start one block immediately after finishing another, they were strongly encouraged to take 5-10 minute breaks between testing blocks.

5.1 Calculation of Scores

Recall that for each trial, an IBOC-FM sample was compared to its matching FM-Only sample. The IBOC-FM sample was randomly assigned to "Sample A" or "Sample B". Participants' rated the samples by directly comparing Sample A to Sample B, but were unaware of which sample was which. Ratings were assigned according to Table 1.

Table 1: Numerical Assignments for Participant Ratings

	Sample A was FM	Sample B was FM
Sample A was much better than Sample B	-3	+3
Sample A was better than Sample B	-2	+2
Sample A was slightly better than Sample B	-1	+1
Sample A was the same as Sample B	0	0
Sample A was slightly worse than Sample B	+1	-1
Sample A was worse than Sample B	+2	-2
Sample A was slightly worse than Sample B	+3	-3

As Table 1 shows, favoring the FM-Only sample yielded a negative score, and favoring the IBOC-FM sample yielded a positive score. Accordingly, in all figures and tables, a negative score means that participants indicated the IBOC-FM samples were worse than the FM-Only samples, and a positive scores means that participants' indicated the IBOC-FM samples were better than the FM-Only samples. For example, in Figure 2, in the no multipath condition, participants rated the audio quality of the IBOC-FM sound samples as 1.2 units lower than the audio quality of the FM sound samples. This means that participants rated IBOC-FM as approximately "slightly worse" than the FM-Only samples.

An analysis of variance (ANOVA) was conducted to see whether the gender of the participant had an effect on the results. There was no effect of gender indicating that males and females rated sound-samples similarly. Thus, gender was removed as a factor for all subsequent analyses.

5.2 Overall performance

Figure 1a shows a histogram of all combined responses. Notice that in 50% of the trials, participants rated the IBOC-FM sound samples as "the same", "slightly better", or "better" than the FM-Only sound samples. However, in 30% of the trials, IBOC-FM was rated "slightly worse", in 14% IBOC-FM was rated "worse" and in 2% IBOC-FM was rated "much worse".

Figure 1a: Participants combined responses (%) (n = 1600)

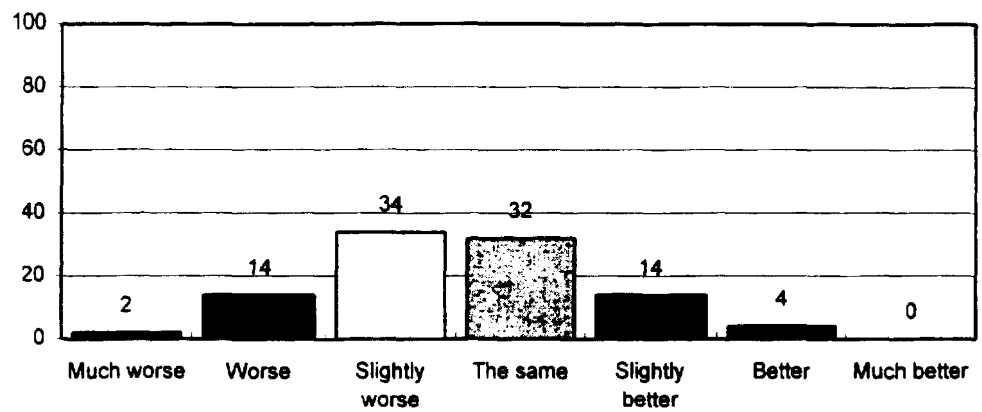
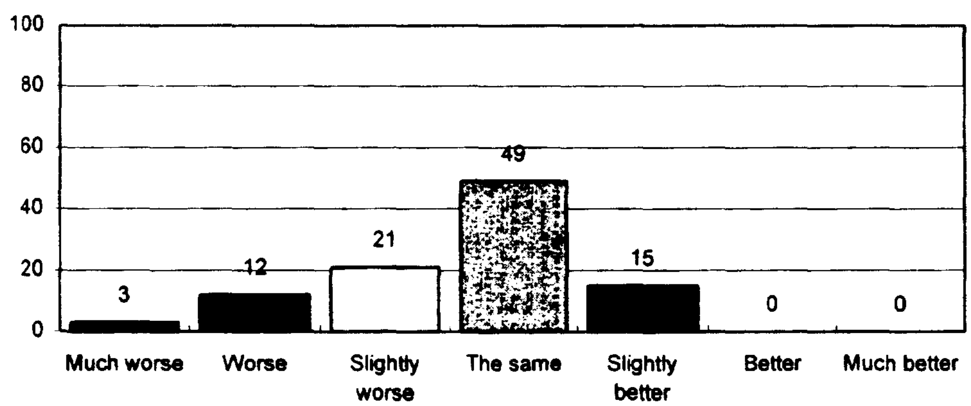


Figure 1b shows the expert listener's combined responses. Surprisingly, the expert listener appears slightly less affected by the impairments than the trained (but not expert) listeners. However, when the categories "the same" and "slightly worse" are combined, the expert's pattern of responses are almost identical to those of the panel of listeners. This implies that the trained listeners remained quite critical throughout the test, and did not relax their standards following the screening procedure. Taken together, these results clearly indicate that the IBOC-FM was rated as the same or slightly better than FM-Only at least half of the time.

Figure 1b: Expert Listener overall responses (n = 100)



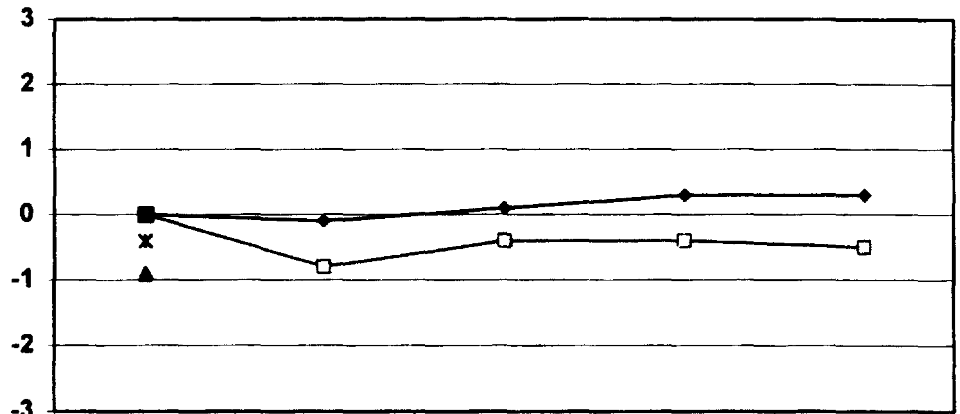
5.3 Performance by Receiver and multipath channel conditions

Figure 2a shows participants' rating of individual receivers. Only three sound samples were included in this analysis: rock, classical and speech. The "silence" sound-sample was not included for two reasons: (a) dead air is not a common phenomenon in typical broadcasting, and (b) the "speech" sample contained silence segments that were more indicative of "real-world" transmission. In the "no multipath" condition, all 5 receivers are shown. In the multipath conditions, only the mobile receivers are shown. Overall, in the no multipath condition, participants rated the FM-IBOC samples -.29 worse than the FM-Only samples. While this number is statistically significant, the small size of the effect suggests that participants heard very little difference between FM-IBOC and FM-Only. Analyzed by radio, participants rated the FM-IBOC and FM-Only samples the same for the *Delphi, Denon,* and *Visteon* receivers, and rated FM-IBOC slightly worse for the *Panasonic* and the *Pioneer*.

In multipath conditions, the overall effect was even smaller for the auto radios. Here, participants rated the FM-IBOC -.13 worse than FM-Only. In both the Urban Moderate Rayleigh and Fast Moderate Rayleigh conditions, participants rated the FM-Only and IBOC-FM the same when received by the *Delphi*, but slighty worse when received by the *Visteon* . In the Rural Fast Rayleigh and Terrain Obstacle conditions, participants rated the IBOC-FM and FM-Only samples the same for both radios.

Again, as Figure 2b shows, while slightly more extreme, the Expert Listener's scores reflect the same trends as seen in the trained listeners' scores.

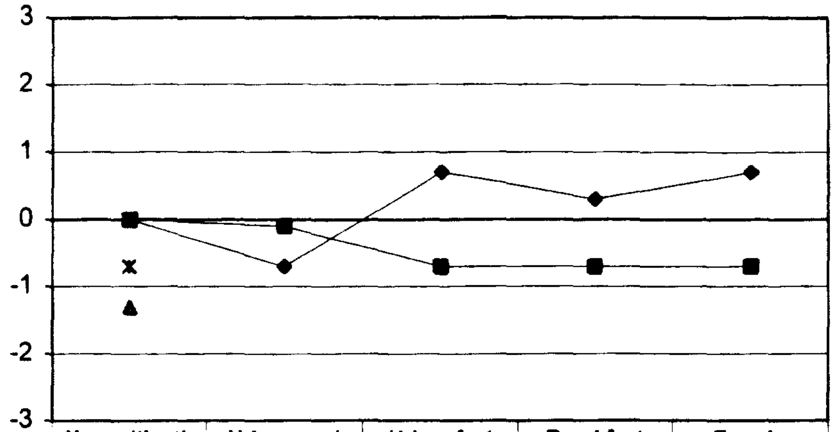
Figure 2a: Audio Quality Ratings by Receiver and multipath channel conditions



	No multipath	Urban mod	Urban fast	Rural fast	Terrain
Delphi	0	-0.1	0.1	0.3	0.3
Ford	0	-0.8	-0.4	-0.4	-0.5
Panasonic	-0.9				
Denon	0				
Pioneer	-0.41				

3 = much better; 2 = better; 1 = slightly better; 0 = the same; -1 = slightly worse; -2 = worse; -3 = much worse

Figure 2b: Expert Listener Audio Quality Ratings by Receiver and multipath channel conditions



	No multipath	Urban mod	Urban fast	Rural fast	Terrain
Delphi	0	-0.7	0.7	0.3	0.7
Ford	0	-0.1	-0.7	-0.7	-0.7
Panasonic	-1.3				
Denon	0				
Pioneer	-0.7				

Appendix 1

Participants % correct score on Pre-Screening Test

Participant ID#	Score (%)
CH00003	100
DS10008	96
EB00004	96
GM100012	100
HS00006	100
HV00004	90
JC100003	100
JD000015	100
JM100001	98
JS000010	100
KM00001	98
PP000011	98
RW100005	94
SS100006	100
XK000019	100
ZZ00002	96

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APPENDIX H

LDR FM HYBRID COMPATIBILITY

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There are over 550 million radios in the United States. LDR recognizes that IBOC compatibility with the established base of analog receivers is of paramount importance for the successful introduction of IBOC services. In this report, we consider two scenarios: (1) host compatibility, and (2) first adjacent channel compatibility. LDR has extensively evaluated and is still evaluating various aspects of compatibility.

1. Host compatibility

The introduction of digital sidebands to create a FM Hybrid signal may impact some analog receivers that are tuned to the IBOC analog host. However, based upon the analysis presented here, the impact is slight. The extent of impact depends on the amount of filtering provided in the receiver (e.g. home, auto or portable). Figure H-1 shows the relationship between typical receiver filters and the spectrum of the LDR FM Hybrid signal.

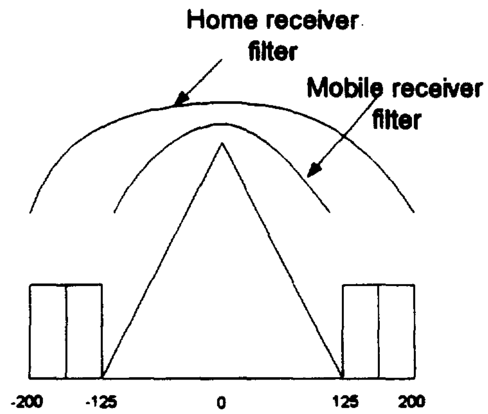

Figure H-1: Example of different FM filter characteristics and the FM Hybrid signal

The appropriate power level of the digital sidebands relative to the FM carrier level and its impact on the host FM signal reception has been extensively researched. LDR has performed rigorous subjective tests comparing the analog audio quality produced by a variety of receivers receiving FM signal with and without IBOC digital sidebands.

The tests were designed to discern any difference and to accentuate the resulting score when even a slightest difference is perceived.

As shown in Appendix G, the extensive subjective tests done with trained subjects in laboratory conditions, using a sample of the population of the FM receivers indicate that at the relative power of –22dB, the degradation is perceived as –0.29 on a 7 point scale. This is roughly equivalent to saying that less that a third of the subjects perceived the degradation as "slight" over the entire range of sound samples and receiver samples. Another observation made was that more than half of the responses indicated the same or better quality with included IBOC signal. The better results may be surprising, however this effect was observed in some mobile receivers under multi-path fading conditions. It is believed that the multi-path effects are somewhat masked by the IBOC signal.

The following figure, reproduced from Appendix G, illustrates the combined results based on 1600 responses. It should be noted that the ACR tests, which are based on human response, always have some spread even if exactly the same audio is played. On average, the responses are almost exactly half way from "the same" to "slightly worse".

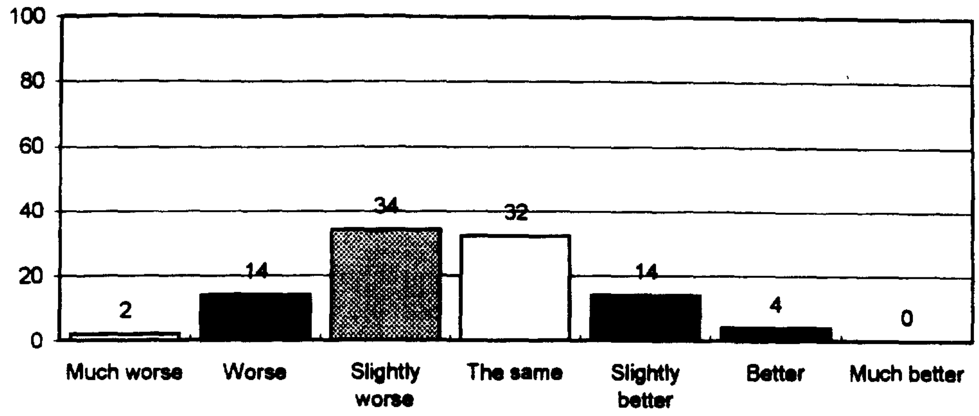

Figure H-2: Participants combined responses (%) (n = 1600)

Based on these results, analog receivers tuned to the host analog signal will not be materially impacted by IBOC. As expected, whatever degradation is observed is more apparent in inexpensive portable receivers than in highly selective automobile receivers.

It should be noted that the 7 point scale using terms such as "the same", "slightly worse", "worse", "much worse", as explained in the appendix, is designed to accentuate the difference. *i.e.* even if the difference is barely perceptible, a participant would give it a relatively large score (zero score is given when no difference is observed at all). There may not be a direct translation from this difference scale to the Absolute Category Rating (ACR) scale typically used in subjective testing. However it is expected that the difference in ACR scores will be much smaller.

2. First adjacent channel compatibility

Another important aspect of compatibility is the impact of the FM Hybrid signal on receivers tuned to the first adjacent analog signal. The results of LDR tests and analysis indicate that this situation does not pose a compatibility problem although it may be expected that in some particular circumstances a small but perceptible degradation may be expected in some receivers.

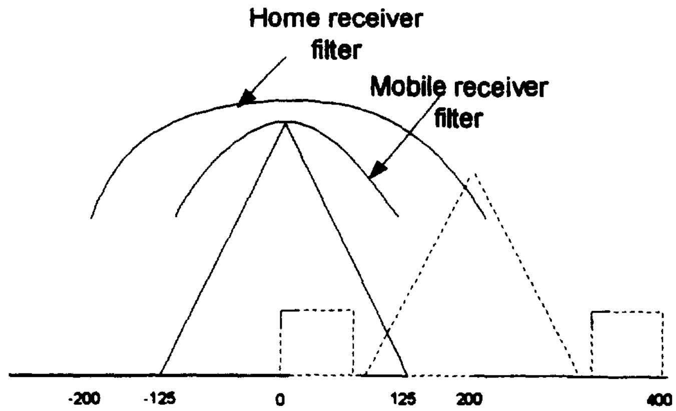

Figure H-3: Relationship between FM filters and a first adjacent FM Hybrid signal at the protected contour

Figure H-3 illustrates relationship between the desired signal and the first adjacent interference at the protected contour. In the figure, the desired analog signal receives energy from the left digital sideband of a first adjacent FM Hybrid signal. At the protected contour, the first adjacent level of the FM carrier is –6dB relative to the desired signal and the digital sideband is –31dB relative to the desired FM carrier.

The question is how much the digital carrier impairs the desired analog signal, and if the impairment is excessive. To judiciously weight the impact, we must use a relative measure i.e. knowing that the analog host of the adjacent channel FM IBOC signal also causes degradation to the desired signal, we need to determine if the digital carrier alone has greater effect than the analog host alone.

The impairment caused by the analog host of the first adjacent channel is different in different receivers. Thus, we need to use a representative sample of the FM receiver population to evaluate the impairments. We have performed limited receiver tests related to the first adjacent performance, however there is a large body of published data available from CEMA regarding receiver performance. Our analysis is based on this data.

CEMA[1] reports that, on average, in non-mobile receivers, the first adjacent (analog) carrier has to be at –22dB below the desired channel in order to produce 45dB output signal to noise ratio (SNR). The best 25% of the receivers (best mobile receivers) require about 0dB. For the average non-mobile receiver, if the first adjacent is placed at –22dB (below the desired FM signal) the digital carrier is –47dB below the desired FM carrier. By itself, this impairment would result in approximately 57dB output SNR. This means that the first adjacent digital carrier produces, on average, significantly less (12dB) impairments than the first adjacent analog carrier. For the highly selective mobile receivers this is changed. *I.e.*, at the protected contour the first adjacent host can be at -6dB relative level, at which the digital carrier is at –31dB. By itself, it results in approximately 41dB output signal to noise ratio. This may cause perceptible change in some mobile receivers at the vicinity of the protected contour in the presence of strong first adjacent channel interference. However, as it is apparent from the subjective tests, the mobile receiver reception is quite degraded at some of these locations even without the first adjacent interference, *i.e.* due to multipath fading. It may seem paradoxical that the some receivers, mostly the expensive auto receivers, suffer degradation while other recivers are immune. However we are measuring degradation relative to that caused by the analog first adjacent signal. Auto receivers are more selective and reject much more of the first adjacent analog signal than other receivers and thereby establish a lower reference point for the impairment due to IBOC digital carrier.

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[1] Consumers Electronics Manufacturing Association, 1999, *"FM Receiver Interference Tests – Laboratory Test Results"*

The fact that most receivers, i.e. home, portables, etc., are degraded far less by the added digital carrier than by the analog host itself indicates that the effect of interference added by IBOC digital signal is at a much lower level than is presently tolerated from other sources.

It should be pointed out that this potential effect can only occur in some mobile receivers in vicinity of the protected contour where the reception is already strongly degraded due to the multipath fading.

Consequently, it can be concluded that from the compatibility standpoint the first adjacent channel interference does not present a problem for the existing population of the receivers although it can be expected that in some cases small difference may be observed in some mobile receivers.

It should also be noted that while analog *mobile* receivers are affected relatively more by the first adjacent effect, the digital mobile receivers' users stand to gain the most. This is because it is in the mobile environment that the most debilitating impairments for the analog signals occur and that affect much more an analog mobile receiver than they affect the LDR FM IBOC mobile receiver.

APPENDIX I

LDR AM IBOC SYSTEM DESCRIPTION

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Introduction

Designing an AM IBOC digital System is a very challenging task. Every digital communication system is a trade off between data throughput and robustness against channel impairments. LDR's AM Hybrid system design is specifically optimized to provide significantly improved digital audio quality when compared to analog and maximum coverage under a variety of AM channel impairments. The AM All-Digital system design, with higher throughput, achieves better audio quality and coverage with improved immunity to impairments.

LDR's AM IBOC system is made of five basic components: The Multi-streaming PAC audio source coding, the modem (modulator and demodulator), the equalizer and signal enhancement module, the FEC coding and interleaving for robustness to different types of impairments and time diversity achieved through the use of the analog audio by blending.

A critical result, presented in Appendix J, is that with dual first and second adjacent interferers on the same side, a relatively low level of second adjacent interference will significantly limit the performances of the first adjacent canceler. In LDR's design, the digital converge is still not limited due to the Multi-streaming PAC approach. The following description outlines the overall LDR AM IBOC technology and the five main components.

LDR AM IBOC SYSTEM

LDR's AM Hybrid is an expansion of the use of the AM band. The AM and digital signals share the same 20KHz channel. The AM Hybrid signal structure is presented in Figure I-1. The digital signal is divided into three streams, a core stream underneath the AM host signal and two "enhancement" streams on both the upper and lower sidebands. The all digital system, presented in Figure I-2, occupies the entire channel and employs three streams as well.

The core stream will use a quadrature structure similar to AM stereo modulation with the digitally modulated information on the quadrature (Q) channel and the existing AM analog information on the In phase (I) channel. The upper and lower enhancements occupy both the I and Q channels. The three audio digital streams are independent in terms of the error correction scheme, such that if one of the enhancements is totally jammed the other two streams will not be affected.

For all the test results submitted in this document, the AM analog modulation was limited to +/- 4.5KHz. We believe that this is the best trade-off between analog and digital audio quality. However the design provides flexibility for the broadcaster to choose the different trade-off between analog bandwidth and digital throughput.

For the AM Hybrid mode, the modulation scheme is 32 QAM . This yields a throughput of 48Kbps. The modulation rates can be varied depending upon the channel conditions and day night operation. The all digital system uses 32 QAM in all streams and yields a throughput of 64Kbps.

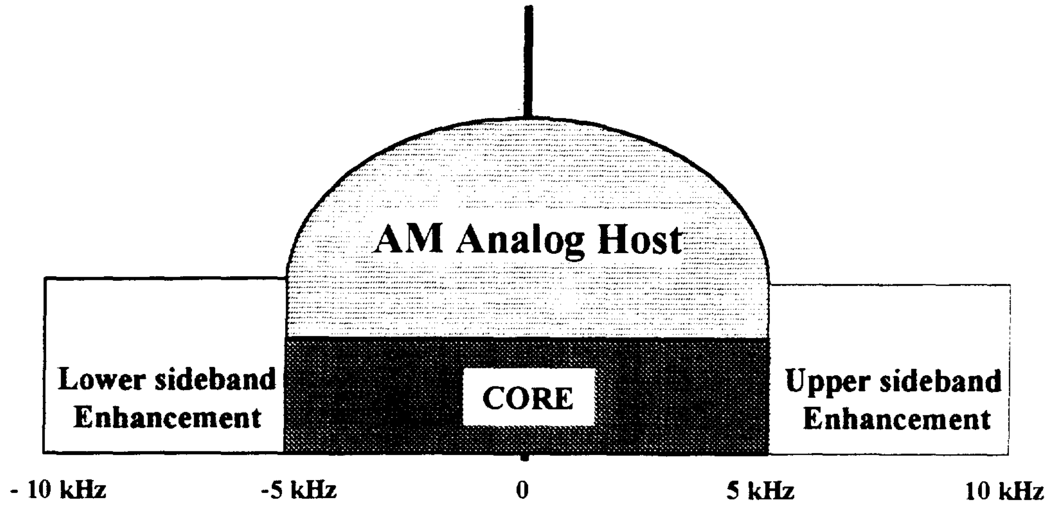

Figure 1-1: AM Hybrid Spectral Occupancy

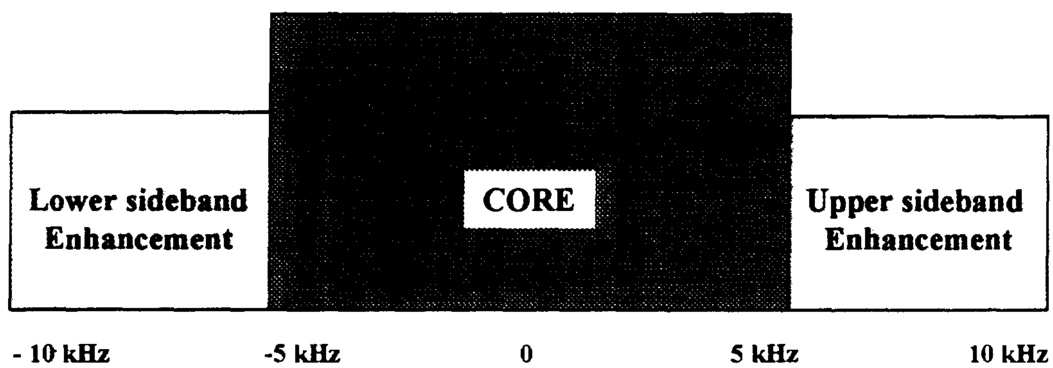

Figure 1-2: AM All-Digital AM Spectral Occupancy

Multi-streaming PAC (Perceptual Audio Coder) for AM IBOC

The limited AM channel bandwidth, the tight spacing between AM stations and existing protection rules in the AM band require a unique solution for the audio coder. Unlike the FM Hybrid system, the AM channel does not provide enough bandwidth (20KHz) to employ the multi descriptive approach to Multi-streaming PAC. The limited bandwidth is not enough to split the audio into two independent streams with good audio quality as is designed in the FM IBOC system. However, an alternative Multi-streaming PAC technique can be employed called Core and Enhancement, which is effective against adjacent channel interference.

Existing protection rules are such that the first adjacent can be as high as -6dB relative to the desired signal. Any one first adjacent channel can interfere with either the upper or the lower digital sideband. To prevent a total loss of the digital signal caused by such interference the AM Multi-streaming PAC provides three streams; a core stream with the primary audio quality and two enhancement streams transmitted on the upper and lower digital side bands. The core provides good audio quality while the enhancement streams increase the audio quality. With this design, a single first adjacent interference will affect only one enhancement stream and will enable the core to recombine with the remaining enhancement. This core and enhancement Multi-streaming PAC scheme improves the robustness of the digital signal under severe first adjacent interference Within the protected contour the core stream is relatively well-protected (-20dB), thus it is possible to receive the core outside the protected contour and in severe interference scenario.

Because the limited AM channel bandwidth does not allow us to employ multi-descriptive techniques (as the FM IBOC system employs), time diversity can not be achieved with the AM band digital signal. To achieve the required robustness from time dependent channel conditions, time diversity in the AM IBOC is achieved through the use of the analog signal by switching to the analog when the digital signal is severely faded.

As in the FM system an advanced error concealment technique is used to improve audio quality even when a significant number of frame errors do occurred.

The Modem

In order to provide enough digital throughput to significantly improve AM audio quality an efficient modulation must be chosen. Quadrature Amplitude Modulation (QAM) was chosen for the following reasons: modulation rates can be modified for day versus night operation as well as for AM Hybrid versus AM All-digital; a high spectral efficiency (bit/hertz) can be achieved, and the linearity requirements for QAM are similar to those for analog AM modulation.

To control interference to the host and to achieve robustness under different channel impairments, OFDM modulation with relatively high number of carriers was chosen. OFDM modulation technique allows maximum use of the given bandwidth with minimum interference to the adjacent channel. The long integration of the OFDM modulation allows for the design of an efficient analog audio cancellation technique especially developed for the AM IBOC system. The same OFDM parameters are used for both the AM Hybrid and AM All-Digital systems. However the AM All-Digital system will employ a higher modulation scheme on the core portion of signal thereby increasing the throughput to 64 Kbps.

Forward Error Correction and Interleaver

A special blend of forward error correction techniques and interleaver are used to further improve the robustness of the system. Each one of the three audio coded streams has its own

FEC and interleaver mechanism allowing optimal performance even in the random interference experienced in the AM band. The FEC is especially designed to match Multi-streaming PAC in term of error detection and correction to improve audio quality under error conditions.

Equalizer and Signal Enhancement Algorithms

To achieve the required coverage coherent detection is designed at the receiver. Coherent modulation, especially multi level QAM, is highly sensitive to rapid changes of phase and amplitude across the channel band. Those rapid changes are caused in the AM band by grounded conductive structures. To correct for those changes a channel equalizer is designed at the receiver end.

The same equalizer is used efficiently to enhance the digital signal relative to the analog host and the first adjacent interference. This enhancement technique is very efficient against analog first adjacent interference as is seen in the lab test results. However the cancellation of the first adjacent is less efficient in the presence of a second adjacent interference even at relatively low level and thus the importance of the Multi-streaming PAC techniques to achieve the required coverage of the digital signal in the AM IBOC system.

Time Diversity

To achieve robustness in mobile environments, time diversity is needed. As mentioned earlier, the AM bandwidth is too narrow to allow multi descriptive audio encoding. Thus, the analog signal is used to achieve the required time diversity. The same audio content is transmitted simultaneously in the analog and digital signals. A time delay, corresponding to the processing delay of the digital signal, is applied to the analog channel at the transmitter. In cases where there is a deep fade, the digital signal continues to be used to produce audio. If the fade is less than the delay, the gap is filled by the analog signal.

AM Hybrid Transmitter and Receiver

A functional block diagram of the AM Hybrid transmitter and receiver are given in Figure I-3 and I-4 respectively.

LDR is working with the major AM transmitter manufactures including Harris and Nautel to ensure a design that can be implemented at low cost. The linearity requirements of many existing AM Transmitters are consistent with the linearity requirements of AM IBOC. Thus the existing transmitters can be used to transmit an AM IBOC signal by combining both the AM analog and AM IBOC signals at low levels and then passing them through the existing AM transmitter. An AM IBOC exciter with audio coder will need to be added to the existing broadcast chain.

AM Hybrid Performance

Based on the test results presented in Appendix J, under unimpaired channel conditions the digital coverage with high audio quality is close to the analog coverage for most receivers. At -92dBm (the average analog receiver sensitivity threshold), all the three digital streams are received (See Table K-2). At the same point in coverage, most existing analog receiver have an audio signal to noise ratio that is close to the Point of Failure.

Performances in presence of noise

In high levels of white noise, the required AM host signal to noise ratio to receive the digital signal is 31dB (see Table K-1). Under such conditions, on average the digital coverage is short 15dB compared to the analog. However, the AM band is dominated by man made noise, which is characterized as shot noise. Shot noise, which is short and bursty in nature is handled much better by the digital signal than the analog. The main reasons are the long integration used by the modem and the inherent dynamic range limits found in A/D converters which clip shot noise impact. OFDM modulation combined with FEC and the interleaver provide a much more robust performance under real man made noise than the analog. As a result of these digital system characteristics, the coverage of the digital signals will be similar to the analog coverage in practical situations.

Interference performance

The main impairments in the AM band are co channel and adjacent interference. We proved through lab tests (see Table K-4) that LDR's AM Hybrid design could efficiently handle analog dual first adjacent interference up to the protected contour even in combination with AM Hybrid Host interference's. Moreover we proved the advantage of the multi stream approach in handling a combination of same side first and second adjacent interference (Table K-6). In this case the core and one enhancement are not affected by the interference and a relative high audio quality can still be achieved. Simultaneous AM IBOC strong upper and lower first adjacent interference is the only case where LDR's AM IBOC does not perform as desired. In this specific case the system will blend to analog.

AM All-Digital Performance

In the AM All-Digital mode, the Multi-streaming PAC approach plays an even greater role than in the AM Hybrid mode. In the AM All-Digital mode, the core signal is limited to +/- 5KHz. The power level of the core signal is similar to the AM power level. Thus the core signal will have greater coverage than analog. The side band will remain at the same level as in the AM Hybrid mode. The core of the AM All-Digital mode can handle dual all digital first adjacent up to 3 dB D/U. In the presence of one first adjacent interference, there is high quality audio at 48 Kbps. While with two strong all digital first adjacent, the quality will be good at 32 Kbps. The Multi-streaming PAC approach is most likely the only solution to the AM All-Digital system. The Multi-streaming PAC solution achieves full coverage up to the protected contour. Even with severe first adjacent interference, audio quality remains high with graceful degradation.

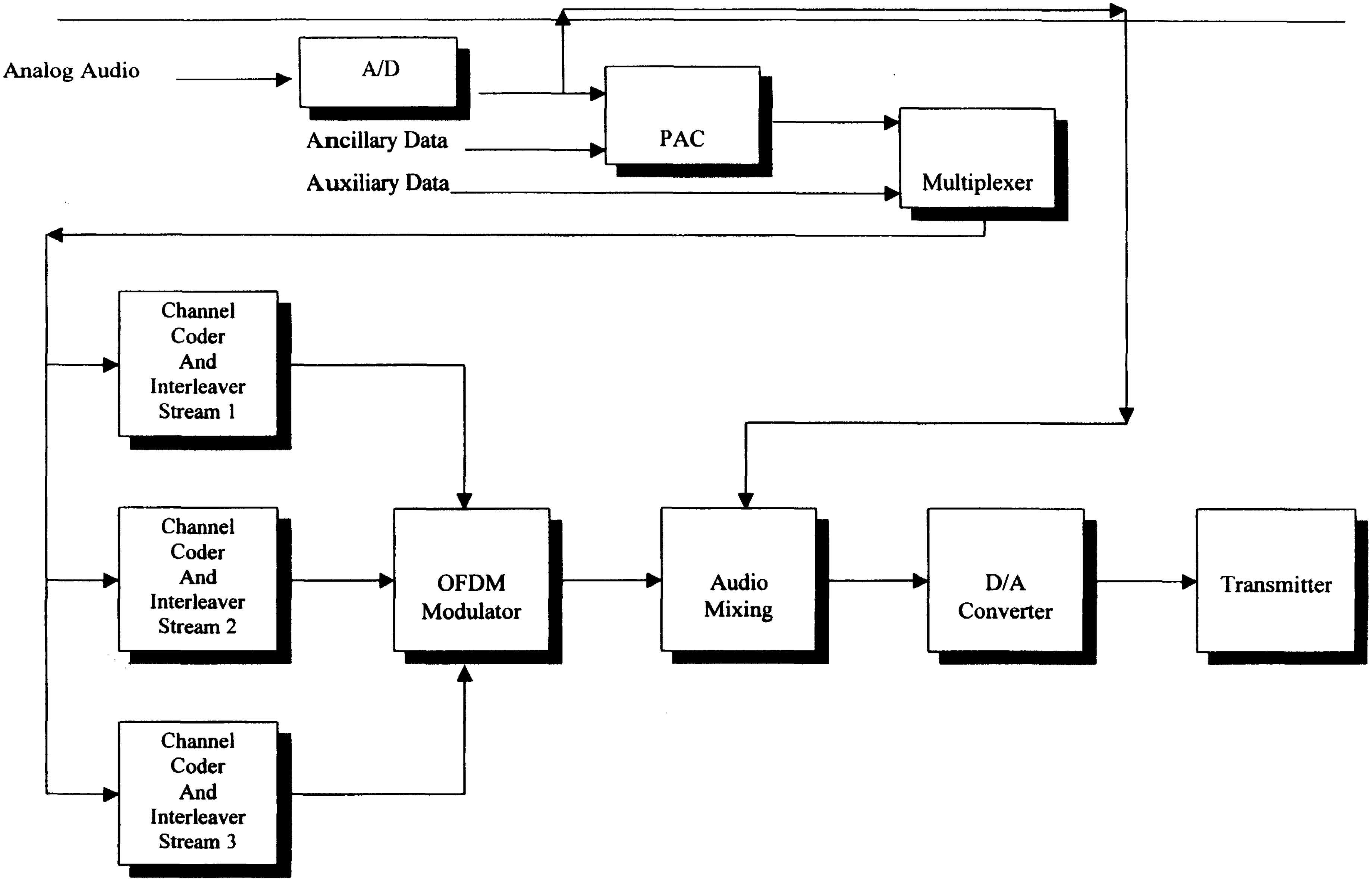

Figure I-3: AM Transmitter Design

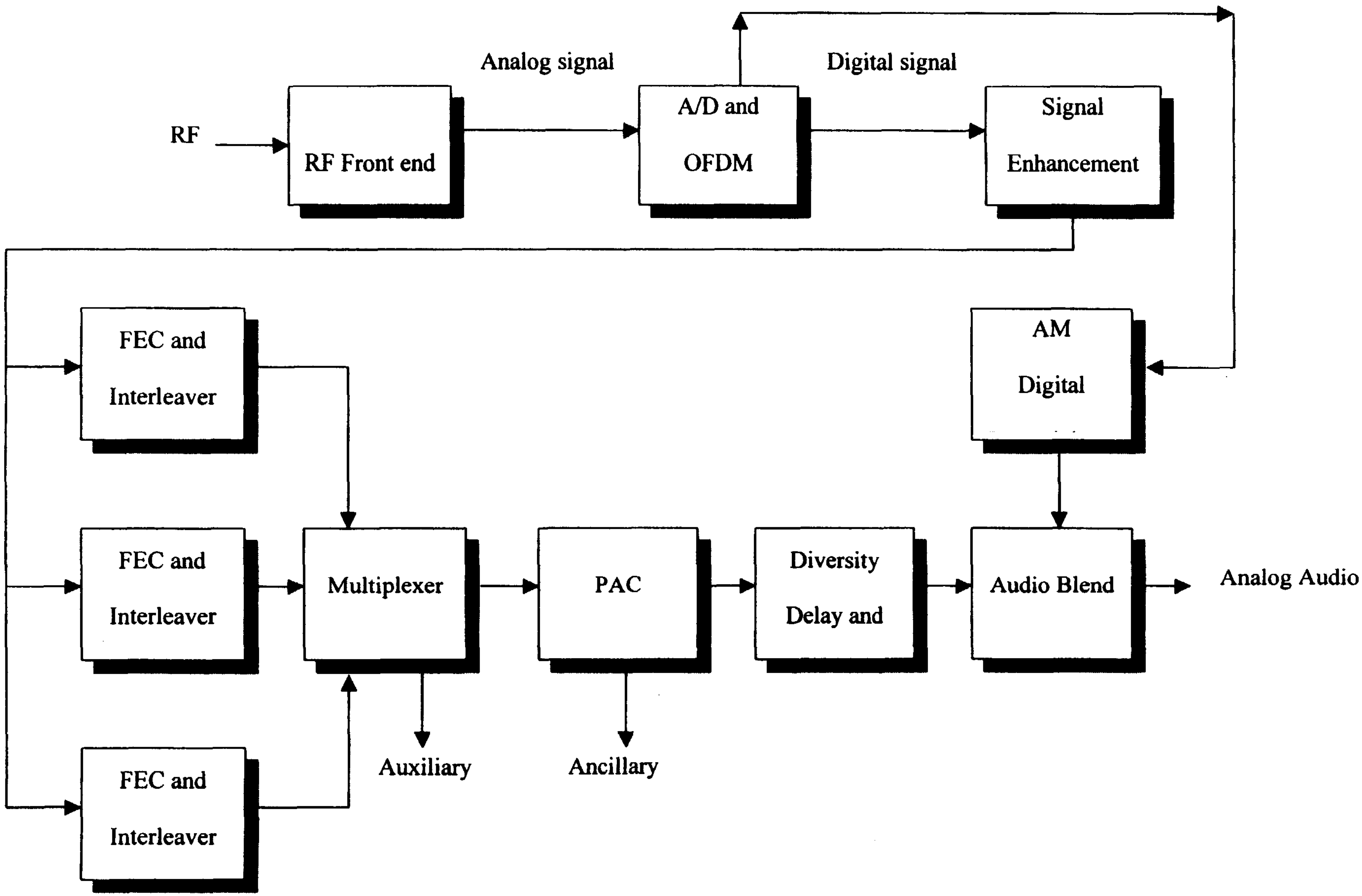

Figure I-4: AM Receiver Design